A 100-KV, 2-KA, 2.5-μS PULSER FOR DEVELOPING AND CALIBRATING LONG-PULSE DIAGNOSTICS*

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Abstract

The development of voltage and current probes [1] for measuring an electron beam's current and position associated with several microsecond-long pulses from advanced Linear Induction Accelerators requires a precision pulser that can deliver both high voltages and high currents to a diagnostics Test Line. Seven-stage, type-E PFNs have been utilized in both a transformer and 4-stage Marx (plus/minus) configuration. The resulting 50-ohm pulser delivers to the Test Line a repeatable 100 kV, ~ 2 μs flat-top (± 1%), 2.5 μs FWHM pulse with a rise time of 500 ns and 175 ns for the transformer and Marx options, respectively. Methods of reducing the rise time for both options are discussed and modeled. The coaxial Test Line is insulated at up to two atmospheres with SF_6 and includes two transition regions to hold and test different diameter beam current and position monitors (BPMs). The center conductor incorporates both translation and tip/tilt with an accuracy of 100 μm. Finally, the line is terminated in a matched radial resistor that provides a planar region at fields up to 40 kV/cm for the testing of voltage probes. Both the transformer and Marx options are modeled and compared to experimental results.

I. INTRODUCTION

The 2nd axis of the Dual-Axis Radiographic Hydro-Test (DARHT) Facility will initially deliver a 2-μs-long electron beam pulse at 2 kA and 20 MeV to a pulse kicker. In order to diagnose the electron beam behavior and provide reliable and repeatable accelerator operation, diagnostics are being developed in a manner similar to that done for the 1st axis which provides a much shorter 100-ns, 4-kA pulse at 20 MeV [2,3]. Of particular importance is the measurement of the ~ 2-μs, flat-top portion of the pulse to a precision of ± 1% for current and ± 100 μm for position at a nominal current of 2 kA. The Test Line and Diagnostics Pulser form the basis of a calibration stand to develop and calibrate beam current and position monitors (BPMs) under similar conditions and geometries to that in the accelerator.

The requirement that the Test Line be capable of being pulsed and swept with commercial instrumentation; that it be connected to the pulser with a single, flexible, plug-and-jack type high-voltage cable; and that voltage breakdown criteria be very conservative led to making the impedance of the line 50 ohms. Although the goal of the of the 2nd axis pulsed power drive and resulting induction cell voltages must have an energy spread < 1%, the pulsers described herein have purposely been tuned to only the few percent flatness level. The resulting modulation on the current serves to exercise the fidelity of the diagnostic. The pulsers also have the provision to peak the front edge of the pulse ~ 10% to check for diagnostic overshoot with reduced rise time.

II. PFN DESIGN

Seven-stage PFNs in a type-E configuration [4] were chosen for the transformer and Marx types of drivers to the Test Line. This choice allows the front and rear edges of the pulse to be independently "peaked" to accommodate the drive cable and load characteristics. Five PFN sections as suggested in [4] with a continuous long-solenoid coil that is tapped to provide the appropriate inductance per section make up the core of the pulse. The governing equations for this type of design, where Lt and Ct are the total inductance and capacitance of the PFN, are given by:

$$\text{Pulse Length (FWHM)} \sim 2\tau = (LtCt)^{1/2} \tag{1}$$

$$\text{PFN Impedance} = Z = (Lt/Ct)^{1/2} \tag{2}$$

$$\text{Coil Inductance} = L \text{ (in uH)} = 0.0984(Na)^2/(4.5a+10b) \tag{3}$$

$$\text{Mutual Inductance} = M = (L_{12} - L_1 - L_2)/2 \tag{4}$$

$$\text{Coupling Coefficient} = k = M/(L_1L_2)^{1/2} \tag{5}$$

In order for the mutual inductance between the coils of each section to be near the classic value of 0.15 of each coil's inductance as suggested in [4], the coil sections need to have an aspect ratio of diameter/length or (a/b) near unity. The coils become more loosely coupled as the pitch is increased. The effect of increasing the coupling (k) between any pair of coils (L_1, L_2, etc.) reduces ripples in the flattop portion of the pulse, increases the PFN impedance, and lengthens the pulse. For near equal coil inductances (i.e. L_1=L_2, etc.), k becomes equal to the desired mutual inductance fraction. Coil inductances

* Work supported under the auspices of the United States Department of Energy.

0-7803-5498-2/99/$10.00©1999 IEEE.

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE	2. REPORT TYPE	3. DATES COVERED
JUN 1999	**N/A**	**-**

4. TITLE AND SUBTITLE
A 100-KV, 2-KA, 2.5~Ps Pulser For Developing And Calibrating Long-Pulse Diagnostics

5a. CONTRACT NUMBER
5b. GRANT NUMBER
5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

5d. PROJECT NUMBER
5e. TASK NUMBER
5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Los Alamos National Laboratory Group DX-8, Mail Stop P939 Los Alamos, New Mexico 87545

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES
See also ADM002371. 2013 IEEE Pulsed Power Conference, Digest of Technical Papers 1976-2013, and Abstracts of the 2013 IEEE International Conference on Plasma Science. Held in San Francisco, CA on 16-21 June 2013. U.S. Government or Federal Purpose Rights License.

14. ABSTRACT
The development of voltage and current probes [l] for measuring an electron beams current and position associated with several microsecond-long pulses from advanced Linear Induction Accelerators requires a precision pulser that can deliver both high voltages and high currents to a diagnostics Test Line. Seven-stage, type-E PFNs have been utilized in both a transformer and 4-stage Marx (plus/minus) configuration. The resulting 50-ohm pulser delivers to the Test Line a repeatable 100 kV, - 2 us flat-top (z!z I%), 2.5 us FWHM pulse with a rise time of 500 ns and 175 ns for the transformer and Marx options, respectively. Methods of reducing the rise time for both options are discussed and modeled. The coaxial Test Line is insulated at up to two atmospheres with SF6 and includes two transition regions to hold and test different diameter beam current and position monitors (BPMs). The center conductor incorporates both translation and tip/tilt with an accuracy of 100 urn. Finally, the line is terminated in a matched radial resistor that provides a planar region at fields up to 40 kV/cm for the testing of voltage probes. Both the transformer and Marx options are modeled and compared to experimental results.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			
unclassified	**unclassified**	**unclassified**	**SAR**	**4**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

calculated by Eq. 3, where N is the number of turns, agree within a few percent with the Nagaoka's table derived values of [5]; both cases progressively underestimate the actual inductance as the coil pitch is increased. End correcting tables from [5] used with Eq. 3 give results accurate to a few percent. Voltage breakdown between coil turns and available spacing between the capacitor terminals led to winding the coils with a length b=10.8 cm and a mean diameter of a=5.95 cm. The coils were free standing utilizing tinned, 10-gauge (0.26-mm-diam) wire.

III. TRANSFORMER BASED PULSER

Initially, it seemed attractive to utilize an available Stangenes (#SI-7672) transformer from a DARHT 1st axis Blumlein Charging Unit (BCU) [6] in a thyratron switched PFN configuration. Excess capacitors having a value of 73 nF at 50 kV from the 2nd axis Injector Marx prototype were also available. The turns ratio of the BCU transformer was reduced by removing every other turn of each 44-turn secondary which provided a transformer with the following measured properties at 10 kHz:

Type	2 winding dual-primary
Step-up-ratio	1:5.6
Magnetizing Inductance	65 uH (referred to primary)
Leakage Inductance	1.03 uH (referred to primary)
Secondary Capacitance	~ 100 pF
Voltage Rating	300 kV for 5 μs

The required PFN impedance is $50/(5.6)^2$ or 1.59 ohms; however, Eqs. 1 and 2 give a pulse length of about 1.6 μs which is too short. Two PFNs were ganged in parallel which gave section values of L=660 nH, C=73 nF, Z=3.2 ohms, N=4, and k=0.057 from Eqs. 1-5 for a pulse length $2\tau \sim 3.25$ μs. This prototype configuration would also allow an individual thyratron to switch each PFN into each winding of the dual-primary as was done in [6]. The resulting parallel PFN driven transformer configuration is shown in Fig. 1 and was tested and tuned at low voltages utilizing Harris RFG70N06, N-Channel Power MOSFETs (70A, 60V, 0.014 ohms, tr ~ 50 ns).

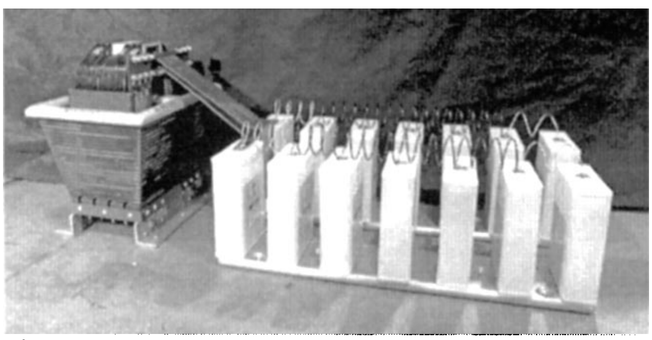

Figure 1. Parallel PFNs driving modified transformer.

Initial testing revealed that the transformer needed to be fully peaked by the front capacitor (no inductor) to partially compensate for the leakage inductance as shown in the simplified schematic of Fig. 2. The rear inductor was reduced from 4 to 2 turns to boost the rear portion of the pulse. The output of the transformer was connected to the load using 30.5 m (195 ns) of Dielectric Sciences DS-2212 Ethylene Propylene Rubber (EPR) flexible x-ray cable having a measured impedance of 52.5 ohms. The resulting flattop portion (~ 2 μs) of the pulse is shown in Fig. 3 and is mostly due to the center 5 stages of the PFN.

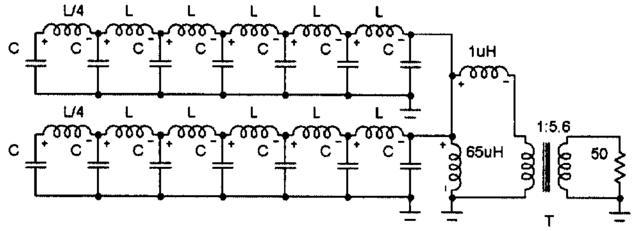

Figure 2. PFNs driving 50-Ω load via 1:5.6 transformer.

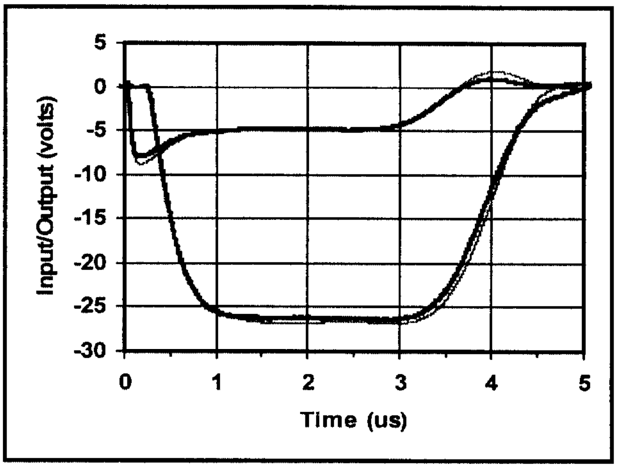

Figure 3. Transformer input/output using MOSFETs.
(the light/thin lines are the Micro-CAP V simulations)

At 10 V charge on the PFNs, the input initially peaks but later is matched at 5 V as shown in Fig. 3. The peak input does not reach 10 V due to the 50 ns rise time of the MOSFETs and the finite inductance (~ 75 nh) of the stripline connecting the PFNs to the transformer input. Although the flattop portion of the pulse is within ± 0.5% over 2 μs, the 500 ns rise time of this configuration is not acceptable for the present application. An optimized transformer with lower leakage inductance could be achieved using the methods of [7] since the voltage rating needs to be only 100 kV and not 300 kV. An additional technique to reduce the rise time consists of independently charging and switching the first capacitor of the PFN at higher voltages.

Micro-CAP V [8] was used to model the circuit. Fig. 3 shows that the simulations agree very favorably with the data; the actual circuit appears to have more losses than accounted for in the model used. Simulations for a factor of 2 reduced leakage inductance and for the first PFN capacitor charged 45% higher are each shown in Fig. 4 with rise times reduced to 350 ns and 300 ns, respectively. Either or both techniques might work with more careful tuning of the PFN; but instead, it was decided to build a PFN Marx system with custom capacitors.

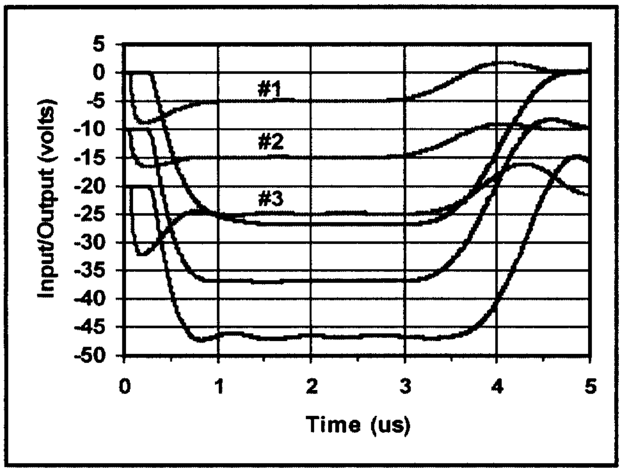

Figure 4. Simulations of reference (#1), reduced leakage inductance (#2), and increased charge voltage on output capacitor (#3). (traces displaced vertically for viewing)

IV. MARX BASED PULSER

Custom, double-ended, plastic-cased, capacitors with a nominal value of 15nF rated at 50 kV were decided upon after much iteration of Eqs. 1-5. These capacitors were connected in a 4-stage Marx (plus/minus) configuration as shown in Fig. 5. The required PFN impedance per stage is 50/4 or 12.5 ohms; however, a slightly lower impedance ~ 48 ohms was chosen. This allowed a ~ 500 ohm resistor across the output that could be used to both trim the impedance presented by the DS-2212 cable as well as serve as a voltage monitor. Using C=15 nF and N=8, gives L=1.93 uH per section; the other values become Z=11.3 ohms and k=0.095 from Eqs. 1-5 for a pulse length $2\tau \sim 2.38$ µs. Once again, a single 7 section PFN was built and tested using the MOSFETs. This data gave Z=11.35 ohms, measured Ls slightly lower at 1.85 uH, and Cs with a measured value of 15.18 nF. The best tune (lowest rise time without overshoot) utilized N=8 inductors for all stages except the output where N=11.

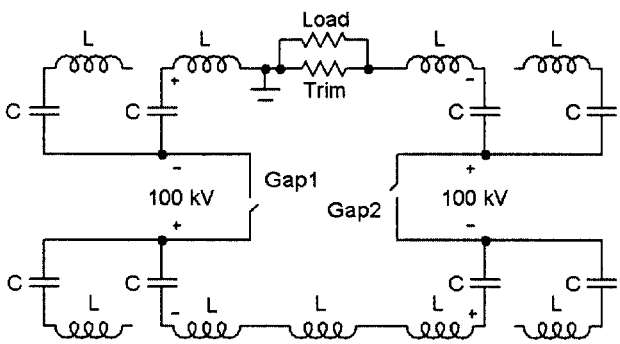

Figure 5. Four-stage Marx PFN configuration.

The Marx utilized two Maxwell, UV-irradiated, 40464 gaps that had been modified for use on the DARHT 2nd axis Injector Marx. Initial tuning was adjusted with the Marx charged to ± 20 V using a MOSFET across each spark gap. Referring to Fig. 5, 7-turn inductors were each located at the pulser's ground and output connections with a remaining 25 turns between the common connected PFNs. These inductors were not mutually coupled to those of the PFNs. A reasonable pulse (see Fig. 6) was achieved with the 39 total turns as opposed to the expected 44 from single PFN tests. A 50-ohm dummy load was constructed of four, 200-ohm, 45-cm x 2.5-cm diameter "Globar" type ceramic resistors immersed in oil. The load also contained a voltage divider and is shown with the pulser in Fig. 7.

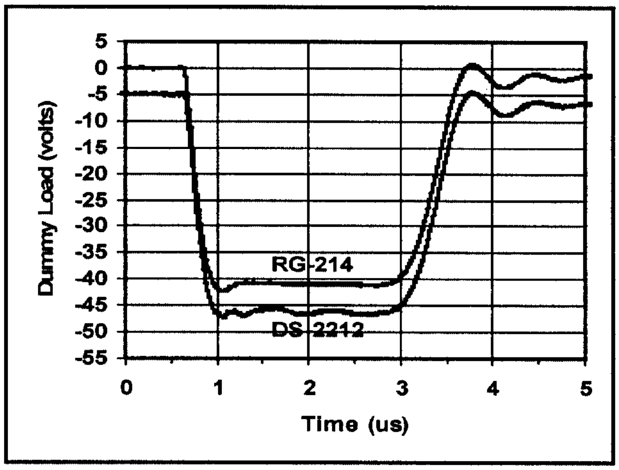

Figure 6. MOSFET tuning at ± 20 V charge with RG-214 and DS-2212 cables and a 1000-ohm "trim" resistor.

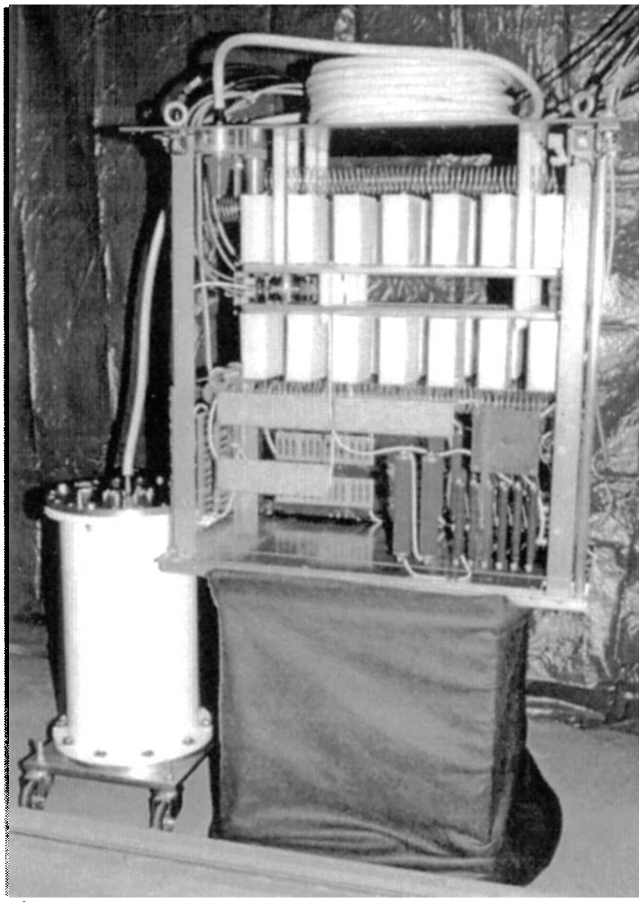

Figure 7. Marx PFN pulser connected to dummy load.

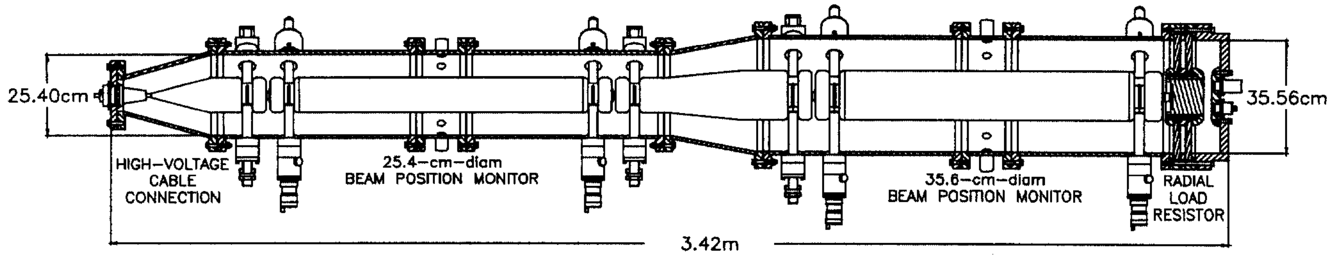

Figure 9. Diagnostics Test Line and Radial Resistor.

Referring to Fig. 6, the DS-2212 cable had much more modulation on the flattop than that of the RG-214 cable. Some improvement was attained by lowering the trim resistor to 500 ohms providing a better match to the slightly higher impedance DS-2212 cable. The pulse response of the EPR based cable had a two step rise time of 25ns to 80% then another 80 ns to 90%; its amplitude response was down 0.3 db and 2.36 db at 1 MHz and 10 MHz, respectively. The pulser was operated at the full charge voltage of ± 50 kV delivering a pulse into the dummy load with a rise time of 175 ns, FWHM of 2.55 μs, and a flattop of 2.03 μs over which the ripple was ± 2% as shown in Fig. 8. The circuit simulation under predicts the amplitude and ripples and over predicts the lower measured initial peak, which may be due to circuit losses. Fig. 8 also shows the pulse purposely peaked 10% at half voltage by reducing the 25-turn inductor to 15 turns resulting in a rise time of 125 ns.

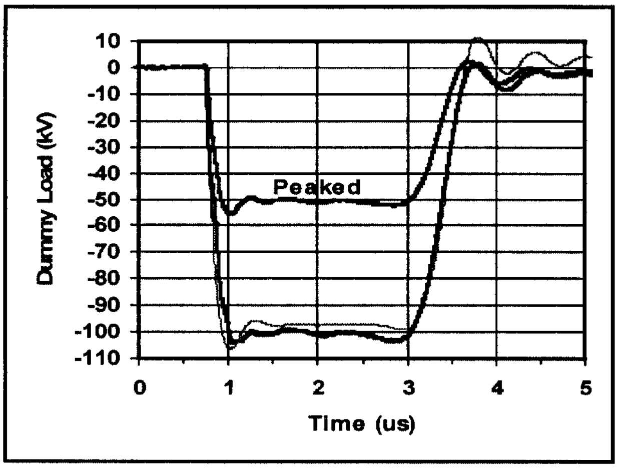

Figure 8. Load voltage of pulser at 25 kV and 50 kV charge with 10% peaking at the lower charge voltage. (the light/thin line is the Micro-CAP V simulation)

V. TEST LINE DESCRIPTION

The Test Line is shown in Fig. 9 and consists of a high-voltage feed with transition, the first test section, another transition, a larger test section, and a radial load resistor that terminates the line. The two test sections hold the nominal 25.4- and 35.56-cm-diameter beam current and position monitors (BPMs). The center conductor incorporates ± 1 cm of translation and tip/tilt with an accuracy of 100 μm. The Test Line is made of 1.27-cm thick aluminum machined from solid billets and can be insulated at up to two atmospheres with SF_6. The highest fields in the line are 45 kV/cm (safety factor of 4 for SF_6) which occur near the planar region after the radial resistor. This region has a very uniform 40-kV/cm field and is used to calibrate field and voltage type probes.

VI. CONCLUSIONS

Both transformer and Marx based, 7-stage, type-E, PFN pulsers have been built and modeled. The 4-stage Marx PFN meets the initial Test Line requirements and is reliable and repeatable at 100 kV with a 2 μs flattop (± 2%) and rise times of 175 ns and 125 ns in the normal and peaked modes, respectively. Minor discrepancies exist between the simulations and the measurements although the cause of the increased ripples when using the DS-2212 cable is not fully understood at this time. The Test Line is still under construction; once complete, the pulser will be tuned with the cable, line, and load as a system.

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